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Interplay of nuclear and Coulomb effects in proton breakup from exotic nuclei

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This paper gives new insight to the study of dynamical effects in proton breakup as compared to neutron breakup from a weakly bound state in an exotic nucleus. To clarify and assess quantitatively which mechanism would dominate the measured observables, we study here several reaction mechanisms separately but also their total effect, including interference. These mechanisms are (i) the recoil effect of the core-target Coulomb potential which we distinguish from the direct proton-target Coulomb potential, and (ii) nuclear breakup, which consists of stripping and diffraction. Direct Coulomb breakup typically gives cross sections about an order of magnitude larger than the recoil term, and the amount of nuclear diffraction vs Coulomb depends on the target. Thus for each mechanism the absolute values of breakup cross sections and parallel momentum distributions for ^{8}B and ^{17}F projectiles calculated on a light and a heavy target in a range of intermediate incident energies (40A–80A MeV) are presented. Furthermore we study in detail the interference among the two Coulomb effects and nuclear diffraction. The calculation of the direct and recoil Coulomb effects separately and of their interference is the new and most relevant aspect of this paper.

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In a previous publication [1] we studied dynamical effects in proton breakup from a weakly bound state in an exotic nucleus on a heavy target. We used a semiclassical method that treats the full Coulomb and nuclear interactions to all orders [2,3]. The dynamics of proton nuclear and Coulomb breakup was compared to that of an *equivalent* neutron of larger binding energy in order to elucidate the differences with the well understood neutron breakup mechanism. We found that with respect to nuclear breakup a proton behaves exactly as a neutron of larger binding energy. The extra "effective energy" is due to the combined core-target Coulomb barrier (see Fig. 2 of Ref. [4]). In Coulomb breakup we distinguished in Ref. [1] the effect of the core-target Coulomb potential (called the recoil effect), with respect to which the proton behaves again as a more bound neutron, from the (direct) proton-target Coulomb potential effect. The latter gave cross sections about an order of magnitude larger than the recoil term. However, the much debated [4] question of the relative magnitude of nuclear and Coulomb breakup was not assessed from a quantitative point of view. This question has been raised again [5] in relation to a study, via the continuum discretized coupled channel (CDCC) method, of the effect of breakup on elastic scattering. We will show in this paper how reaction theory can presently answer such a question.

In fact, in another recent paper [6] in which CDCC has also been used, the authors have shown that our predictions [1] for the proton angular distribution after Coulomb breakup were correct and thus they have validated our interpretation. Such comparison is interesting for two reasons. The first is that CDCC is easier to apply at low energy because the convergency is faster while a semiclassical method like ours works well in the medium-high energy domain. The second is that in our method the interpretation of the results is straightforward because the relative motion between projectile and target is introduced via a semiclassical trajectory and thus the Coulomb and nuclear potential that the breakup particle feels can be treated exactly and approximations can be checked, without disturbing the relative motion treatment. Thus the two methods could be complementary in their applications.

We then proceed in this paper to present the calculated absolute values of the cross sections due to the nuclear and Coulomb breakup (recoil and direct) separately and then show how much the interference effects modify the simple sum of the cross sections. This is very important in view of spectroscopic studies of proton vs neutron rich nuclei Refs. [7–24] and also for the applications in nuclear astrophysics since Coulomb breakup is considered the inverse process of the (p,γ) capture [7]. Results from breakup on a light and a heavy target will be discussed in a range of incident energies from 40A to 80A MeV. The details of the theory can be found in Refs. [2,3].

Table I shows the bound state parameters used in the calculations. Although the calculations are done here with the exact proton wave function we give also the effective binding energies discussed in Ref. [1] to help the reader understand the difference with the neutron breakup. Spectroscopic factors for the initial states are taken equal to unity. For both projectiles, only breakup from the valence state is considered. All other parameters used in the calculations are the same as in our previous papers [1,3].

Table II contains the absolute values of the cross sections for the one proton breakup from ^{8}B and ^{17}F on ^{12}C and ^{208}Pb at 40A, 60A, and 80A MeV. The cross sections due to the stripping and diffraction mechanisms of the nuclear breakup and the direct and recoil terms of the Coulomb breakup are shown separately. We give also the total Coulomb cross sections which contain the interference effects of direct and recoil terms. Furthermore the total elastic breakup (diffraction plus Coulomb) cross sections are given. They contain all interference effects between the three possible mechanisms (nuclear, direct Coulomb, recoil Coulomb) following which the proton would be measurable in coincidence with the core. We remind the reader that nuclear stripping instead is the

TABLE I. Barrier radii, initial binding energies, and effective energy parameters for a ^{208}Pb target.

	^{8}B	J^π	^{17}F	J^π
R_i (fm)	6.0		6.5	
ε_i (MeV)	−0.14	$1p_{3/2}$	−0.6	$1d_{5/2}$
$-\Delta$ (MeV)	−0.4		−1.2	
$\tilde{\varepsilon}_i$ (MeV)	−0.54	$1p_{3/2}$	−1.8	$1d_{5/2}$

mechanism in which the nucleon is emitted by the projectile and undergoes a final state inelastic scattering with the target. It is thus considered absorbed by the target, in the sense of the optical model absorption and its energy degraded such that it would not be detected in coincidence with the core of origin. Such a mechanism cannot interfere with diffraction nor with Coulomb breakup. Stripping is larger than diffraction, as first noticed in Ref. [25].

Parallel momentum distributions due to the Coulomb recoil and Coulomb direct terms from ^{8}B and ^{17}F and their combined effect including interference are shown in Figs. 1 and 3, respectively, while Figs. 2 and 4 show parallel momentum distributions due to nuclear and Coulomb breakup from the same projectiles and their total effect including interference. Notice that in Fig. 3 some asymmetries appear due to the interference of the direct and recoil Coulomb effects.

In the case of the ^{8}B projectile at 40A MeV incident energy on the ^{208}Pb target both the cross section values in Table II and Fig. 1(c) show that the direct and recoil Coulomb terms interfere destructively and total Coulomb is almost exactly the difference of the two. Increasing the incident energy, the two Coulomb effects show very small interference and the total is very close to the sum of the two in the total cross section (cf. Table II) while in the momentum distributions shown in Fig. 1(d) at the very small parallel momentum values it is given by the difference of the two with the recoil term just contributing more. The interference between diffraction and Coulomb is also very small and it is destructive or constructive depending on the incident energy on the heavy target, Figs. 2(c) and 2(d). As expected, on the light ^{12}C target the recoil effect is really negligible and the Coulomb breakup is mainly due to the direct term at all incident energies, Figs. 1(a) and 1(b). Thus the interference is small and always constructive. Diffraction cross sections on the other hand have much higher values than Coulomb breakup cross sections for the light target. The interference is so strong at low energy that it almost doubles the simple sum of diffraction and Coulomb breakup, Figs. 2(a) and 2(b). This effect is very interesting and it shows that by including the Coulomb breakup the cross section can increase a lot but not because the Coulomb itself is large, but because of the interference.

In the case of the ^{17}F projectile the effects are similar but the interference, in the cases shown here, is always constructive both between direct and recoil Coulomb as well as between Coulomb and diffraction as can been seen from Figs. 3 and 4.

On the other hand looking at Table II one sees also that for both projectiles the total nuclear breakup cross sections are always of the same order of magnitude than the recoil Coulomb breakup on a heavy target but much smaller than the direct Coulomb and the total Coulomb cross sections. Thus we confirm what has already been suggested by other authors [16,20,26], on why in the past calculated nuclear breakup of a proton has been found comparable to or even larger than the Coulomb breakup. The misinterpretation was simply due to a underestimation of the direct Coulomb breakup due to both the dipole approximation and its treatment to first order and to the fact that interference effects were overlooked. In particular our present results and interpretation seem to corroborate the CDCC calculations and interpretation of Ref. [26], the new aspect of our method being the study of the direct and recoil Coulomb effects separately and of their interference.

In conclusion, in this paper we have presented results of calculations for all mechanisms that can produce breakup of a weakly bound proton from an exotic nucleus impinging on a light and a heavy target. The semiclassical method used allows us to treat both the full nuclear and Coulomb interactions to all orders and all multipolarities. On a light target the total nuclear breakup is always larger than the Coulomb breakup. On the other hand although the Coulomb breakup is very small the interference between diffraction and Coulomb is constructive and such that the total becomes quite large. On a heavy target instead the total nuclear breakup is of the same order of magnitude as the Coulomb recoil effect while the direct Coulomb breakup is one order of magnitude larger. Thus this term dominates not only in the total Coulomb breakup but also in the total diffraction plus Coulomb term. The quantitative assessment of the direct Coulomb breakup and of its interference with other mechanisms is very important and

TABLE II. $\sigma_{\rm bup}$(mb) for nuclear and Coulomb mechanisms as indicated for ^{8}B, $1p_{3/2}$ initial state, and ^{17}F, $1d_{5/2}$ initial state, on ^{12}C and ^{208}Pb targets at $E_{\rm inc} = 40A, 60A, 80A$ MeV.

Target	^{12}C						^{208}Pb					
$E_{\rm inc}$(MeV)	40A		60A		80A		40A		60A		80A	
Projectile	^{8}B	^{17}F	^{8}B	^{17}F	^{8}B	^{17}F	^{8}B	^{17}F	^{8}B	^{17}F	^{8}B	^{17}F
Stripping	51.62	18.06	41.17	13.49	34.79	10.93	105.94	29.97	88.59	23.09	78.16	19.29
Diffraction	31.72	8.19	23.16	5.42	18.86	4.15	70.42	14.08	58.84	10.99	52.39	9.36
Coulomb recoil	0.10	0.007	0.05	0.004	0.03	0.002	534.18	65.98	262.23	31.74	159.09	19.14
Coulomb direct	2.09	0.58	1.01	0.28	0.61	0.17	4562.66	1209.35	2578.76	624.61	1741.04	394.54
Total Coulomb	2.51	0.67	1.21	0.32	0.73	0.19	4129.47	1542.39	2796.84	874.40	1925.34	611.52
Coulomb and Diffraction	60.29	22.79	39.74	13.18	30.89	9.42	4228.56	1608.39	2740.82	956.64	1928.03	691.09

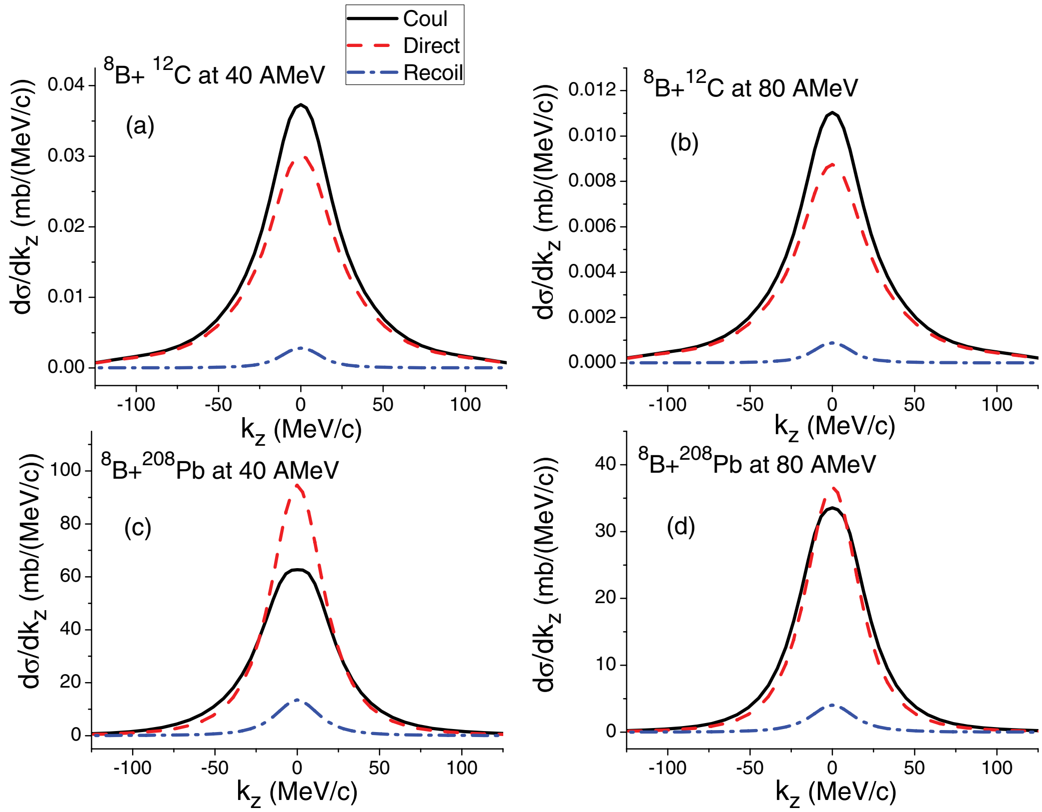

FIG. 1. (Color online) Parallel momentum distributions due to the Coulomb recoil and direct terms from ^{8}B on ^{12}C and ^{208}Pb as indicated and their combined effect including interference.

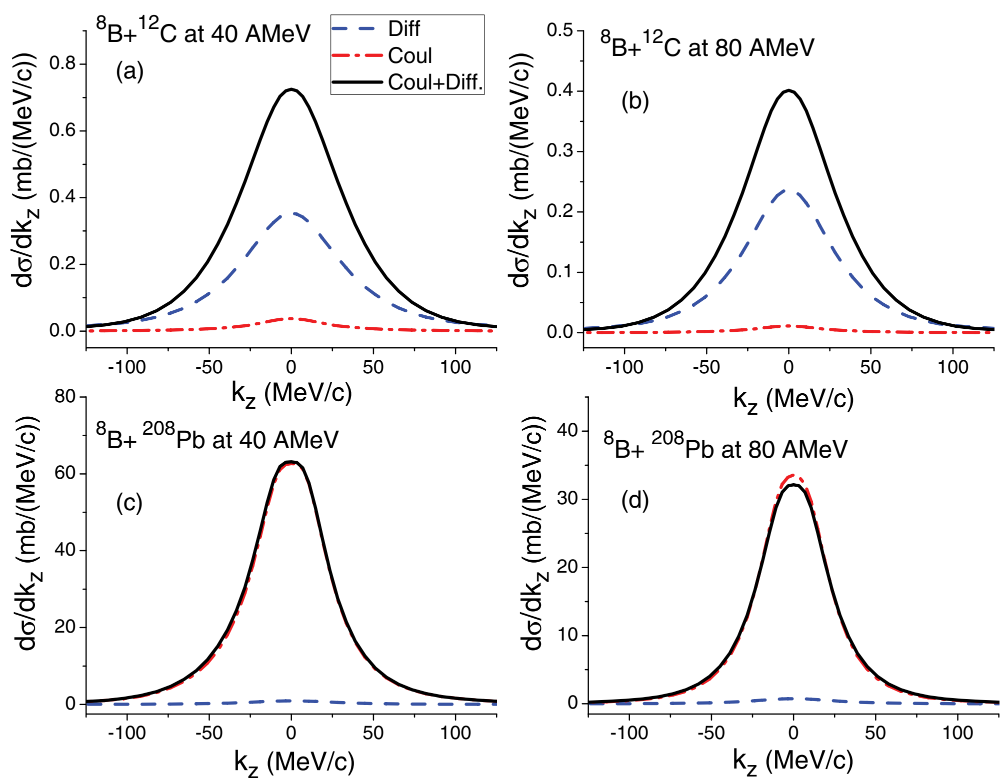

FIG. 2. (Color online) Parallel momentum distributions due to diffraction and Coulomb breakup from ^{8}B on ^{12}C and ^{208}Pb as indicated and their combined effect including interference.

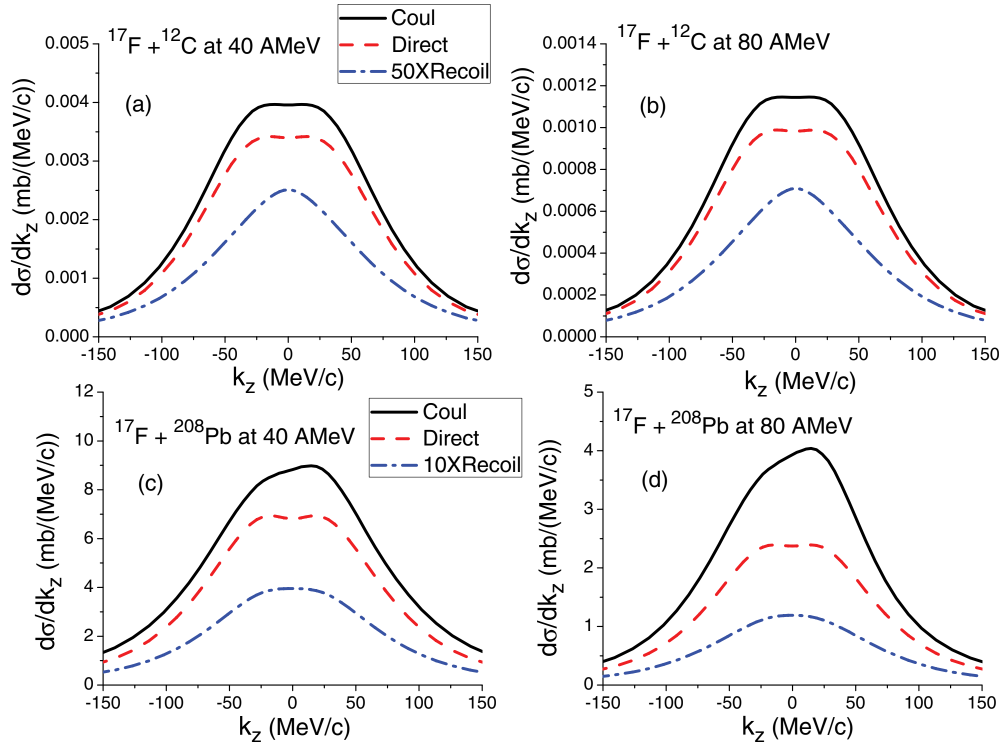

FIG. 3. (Color online) Parallel momentum distributions due to the Coulomb recoil and direct terms from ^{17}F on ^{12}C and ^{208}Pb as indicated and their combined effect including interference.

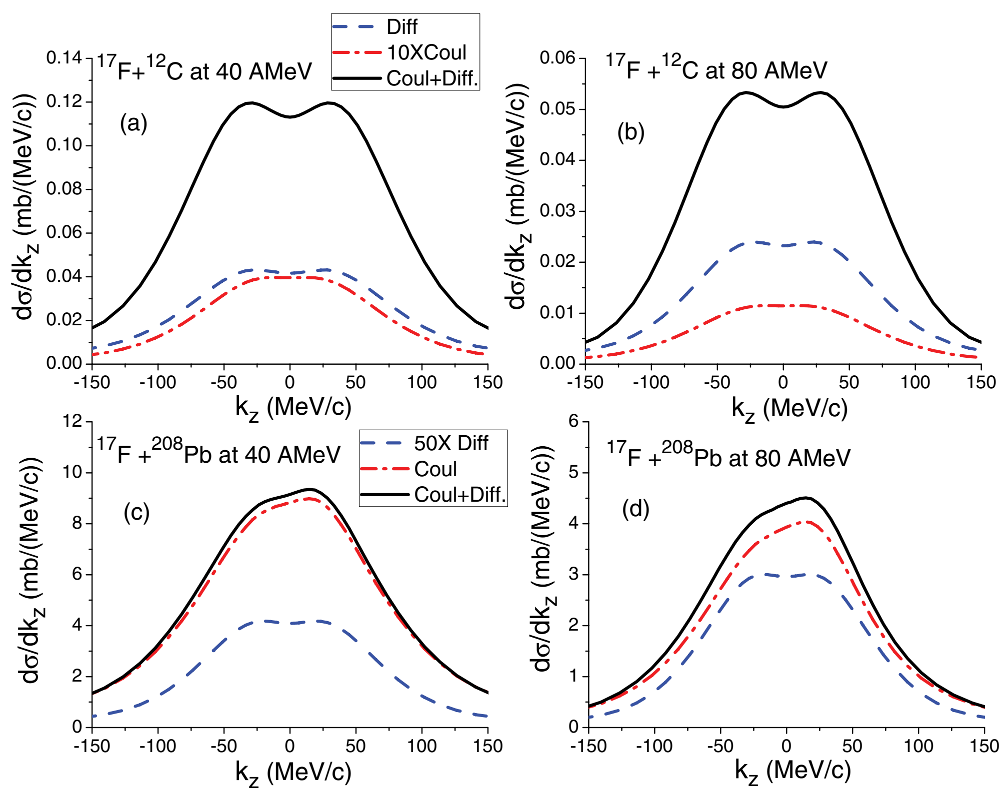

FIG. 4. (Color online) Parallel momentum distributions due to diffraction and Coulomb breakup from ^{17}F on ^{12}C and ^{208}Pb as indicated and their combined effect including interference.

given here for the first time in the literature. It is then clear that the breakup mechanism of a proton is much more complicated than that of a neutron and disentangling various effects is of fundamental importance when interpreting experimental data. Interference effects are somehow impossible to predict without an explicit calculation and as it has been shown above might vary from one observable to the other and very accurate yet simple to interpret reaction models are necessary to analyze data and/or to make predictions in order to plan future experiments. This is particularly true for applications in nuclear astrophysics where Coulomb breakup is considered the inverse process of the (p,γ) reaction. Such a concept will have to be handled with great care in the future. Detailed calculations such as those presented here or made with the CDCC method, depending on the incident energy, should be performed and correctly interpreted in order to assess two aspects: (i) if and which part of the cross section could be considered corresponding to the (p,γ) reaction cross section; (ii) if such separation could be also done by an appropriate experimental procedure and in the data.

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